NATIONAL HURRICANE RESEARCH PROJECT

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the Eye of Intense Typhoons Between
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by

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TYPHOONS BETWEEN THE DEEPENING AND FILLING STAGES

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ABSTRACT

Aircraft reconnaissance observations from the eye of unusually deep typhoons (minimum sea level pressure $\leq$ 900 mb.) indicate that temperature and moisture conditions in the layer between the surface and 700 mb. usually undergo rather large changes at about the time of lowest pressure. Abnormally warm, dry soundings are found almost exclusively during the period that the sea level pressure is falling rapidly. Following the time of lowest pressure, the soundings are quite moist in most instances and lapse rates are very close to the moist adiabatic rate.

The size of the eye also shows systematic changes between the deepening and filling stages of the storm. The eye usually decreases in size as the storm deepens with the minimum value occurring near the time of lowest pressure. Cloud data for the eye indicate quite variable conditions and fail to show clear cut differences between the deepening and filling stages which might be expected from the observed changes in temperature and moisture within the eye.

The temperature changes in the surface to 700-mb. layer offer a relatively small contribution to the observed changes in sea level pressure in tropical cyclones. Although observations are not available for the upper tropospheric portions of the eye, some qualitative statements can be made in regard to the temperature changes in this upper layer by considering the observed temperature changes in the lower layer along with the changes in sea level pressure.

1. INTRODUCTION

For the past fifteen years most tropical cyclones in the portions of the Atlantic and western Pacific Oceans north of the equator have been investigated in a routine fashion by reconnaissance aircraft of the U. S. Air Force and Navy. Much valuable information on the structure of these storms has been provided by the reconnaissance data which consist of visual and instrumental observations made at flight level and of soundings below the aircraft by the dropsonde technique. However, within the zone of strong wind and heavy rain surrounding the eye of tropical cyclones, the completeness and reliability of the visual and instrumental observations made from the operational reconnaissance aircraft leave much to be desired. The observations made in the interior of the eye are, in general, more complete and more reliable since they are made largely in clear air and in areas where horizontal temperature and pressure gradients are relatively weak.

Despite the fact that hundreds of flights have been made into tropical cyclones, there has been very little summary information published in regard to the structure of the eye and its changes during the life cycle of the storm. The fact that the structural features of the eye are quite variable has probably been an important deterrent to the preparation of studies of this type. Flight-level and dropsonde data taken during selected periods have been used for the preparation of mean temperature data for the eye of tropical cyclones [3] [5] but there has been very little summary information prepared in regard to such features as the vertical distribution of moisture, the extent and type of cloudiness, and the size and shape of the eye. Information of this type covering a very special category of tropical cyclones, as presented in this report, illustrates some of the difficulties which would arise in the preparation of a comprehensive summary of the reconnaissance observations from the eye of tropical cyclones.

Mean temperature data for the eye of tropical cyclones obtained from the dropsonde observations (fig. 1) show very clearly that temperatures become warmer and lapse rates more stable in the deeper storms. At levels near the surface, changes are small even in the deepest storms but at the upper levels a marked increase in temperature is found in the storms with very low central pressures. In the extreme cases [12], individual soundings have shown 500-mb. temperatures as warm as 16°C., or nearly 25°C. warmer than mean tropical conditions. The sounding information is limited almost entirely to observations from the 500- and 700-mb. levels and, in fact, there are very few dropsonde observations even from the 500-mb. level in tropical cyclones with very low central pressures.

The indicated warming up to the 500-mb. level in the deepest cases (fig. 1) is, from hydrostatic considerations, adequate to account for only about one-fourth of the observed decrease in sea level pressure [5]. This clearly indicates that large positive temperature anomalies, relative to mean conditions at the individual levels, must exist in the upper troposphere. Little can be said about the warming at upper tropospheric levels since very little temperature information is available above the 500-mb. level and practically nothing is known about the height and character of the tropopause over the center of deep tropical cyclones. Wind and temperature data from rawinsonde
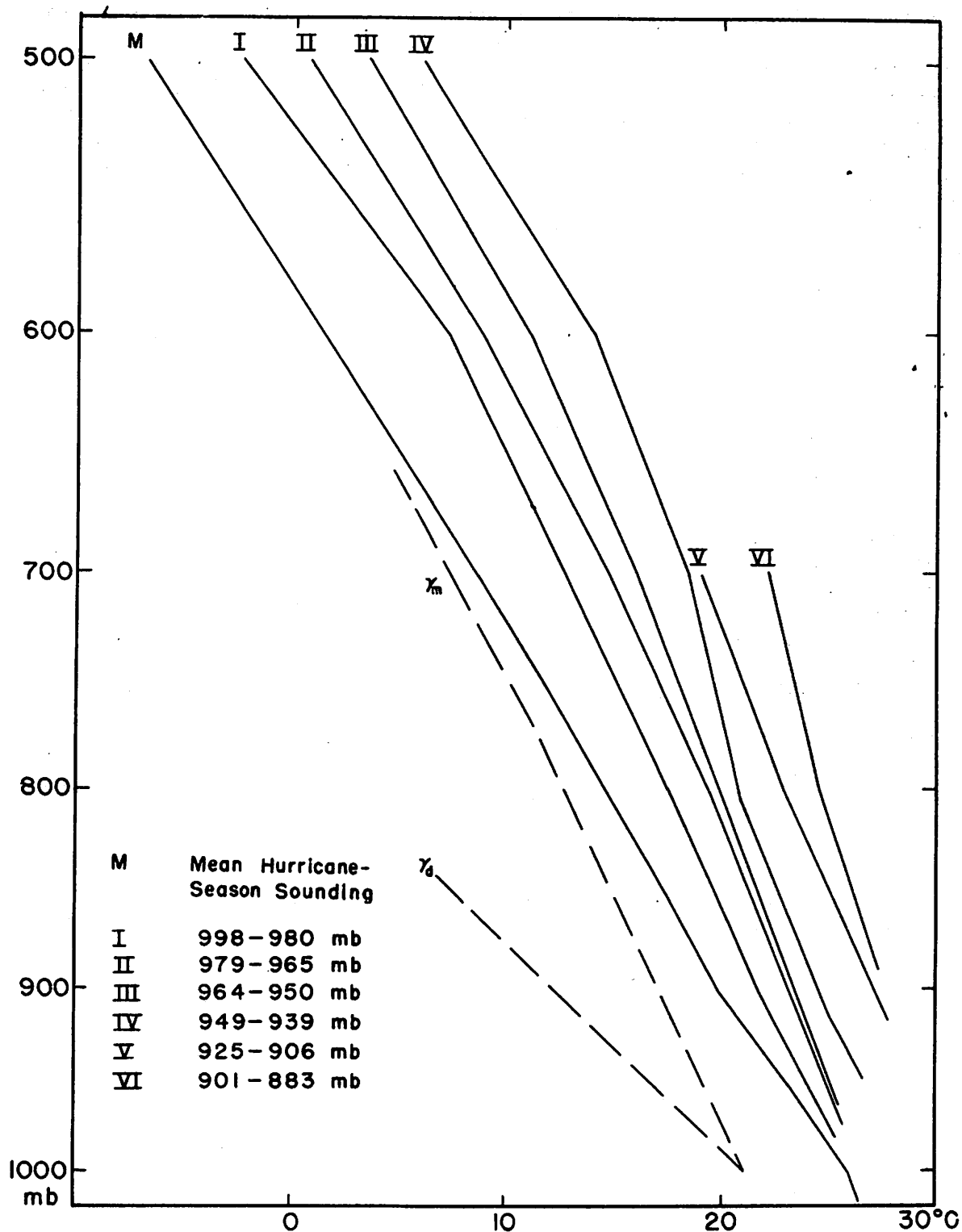
Figure 1. - Mean temperature curves for the six categories of tropical cyclones defined by the surface central pressure ranges shown in the table in the lower left (from [5]). The mean hurricane-season sounding (M) from [6] and segments of a moist adiabat γ_m and a dry adiabat γ_d are also shown.

observations made near the center of these storms suggest that conditions at
the 100-mb. level remain virtually unchanged during the passage of most trop-
ical cyclones [11][2], but in the extreme cases it would appear likely that
the storms may extend somewhat above the 100-mb. level [10]. If the conserva-
tive assumption is made that the deepest typhoons, i.e., those with sea level
pressures near 880 mb., extend to the 80-mb. level, it can be shown that a
mean warming of the 500- to 80-mb. layer of 15°C. above mean tropical condi-
tions would be required from hydrostatic considerations [5]. Any description
of the vertical distribution of the upper tropospheric warming accompanying
the deepening of tropical cyclones must, of course, await high-level sounding
data from the eye of these storms.

The warm conditions in the eye must be attributed in part to subsidence
since the temperatures are much warmer than those observed in the storm en-
vironment or those which could be realized by moist adiabatic parcel ascent
from the surface of the earth. The lapse rates in the eye at middle tropo-
spheric levels depart appreciably from the dry adiabatic rate and the mois-
ture content of the air is often quite high. These facts suggest that there
must be a considerable amount of air mixed across the eye boundary into the
descending currents. In fact, it appears likely [8] [9] that much of this
descending air has ascended in the wall of the eye and has been mixed into
the eye at middle tropospheric levels. It is not known to what extent mix-
ing of the same type may be important at the upper tropospheric levels but,
as discussed below, high-level cloudiness is quite frequent within the eye
even in the most intense storms.

2. INDIVIDUAL SOUNDINGS FROM THE EYE OF DEEP TYPHOONS

The warmest and driest conditions in tropical cyclones are always found
in the eye of storms with very low central pressures. However, not all drop-
sonde observations made in the eye of deep storms show the warm, dry condi-
tions. The marked changes in the character of the eye soundings from deep
storms, often between observations made a few hours apart, have been a
puzzling problem for a long time and an important factor in discouraging the
preparation of mean moisture data for the eye of tropical cyclones. The
changes, as indicated by the dropsonde records, are most marked in the deep-
est storms since it is only in these cases that warm, dry conditions appear
with any regularity at levels below 700 mb.

Observations made six hours apart in typhoon Grace of 1958 (fig. 2)
illustrate the large changes in the vertical temperature and moisture dis-
tributions which have been reported. During this period when the storm was
over the tropical Pacific hundreds of miles from any significant land mass,
the central sea level pressure was reported to have increased from 900 to
915 mb. with the air in the lower portion of the eye becoming cooler and much
more moist. The marked temperature inversion disappeared with an indicated
cooling as great as 13°C. near the 750-mb. level. A nearly moist adiabatic
lapse rate and saturated conditions were shown through a deep layer on the
second sounding in contrast to the earlier observation which showed relative
humidities as low as 25 percent in the vicinity of the 750-mb. level. The
observed cooling below the 700-mb. level in this case, if considered alone,
is adequate for a little more than half of the observed change in sea level
pressure.

Figure 2. - Temperature and dew point curves for two dropsonde observations made in typhoon Grace of 1958 at the times indicated on the diagram. Moist and dry adiabats are shown by the dashed curves. SLP = sea level pressure.

Simpson [12] discussed soundings made five hours apart in typhoon Marge of 1951 which also showed quite large changes in temperature and humidity in the vicinity of the 700-mb. level. In this case, the soundings extended up to the 500-mb. level and there was essentially no change in the extreme upper or lower portions of the soundings. The later of the two observations showed the colder temperatures, principally between 750 and 600 mb., and the lower sea level pressure, which represented the minimum value attained in this typhoon. Therefore, in this case, there must have been warming at levels above 500 mb. which was more than enough to compensate for the cooling observed below this level.

Changes of the type indicated in figure 2 have been viewed with a great deal of suspicion by most investigators, including the author. However, in most cases of this type, no direct evidence could be cited to discredit the observations. Large systematic errors in the dropsonde temperatures can usually be ruled out by the fact that the reported surface temperatures are nearly the same in the two types of soundings. In the case of figure 2, it might be questioned, in view of the increase in sea level pressure and the nearly moist adiabatic lapse rate, whether the second observation was made in the edge of the wall cloud rather than near the center of the eye. There is a further difficulty that instruments descending through clouds within the eye could be expected to give somewhat different temperature and moisture lapse rates than those descending in clear spaces between clouds. Although these factors cannot be ruled out in most individual cases, the relatively cold and moist soundings in the eye of deep tropical cyclones have been reported with sufficient frequency to suggest that changes of the type indicated
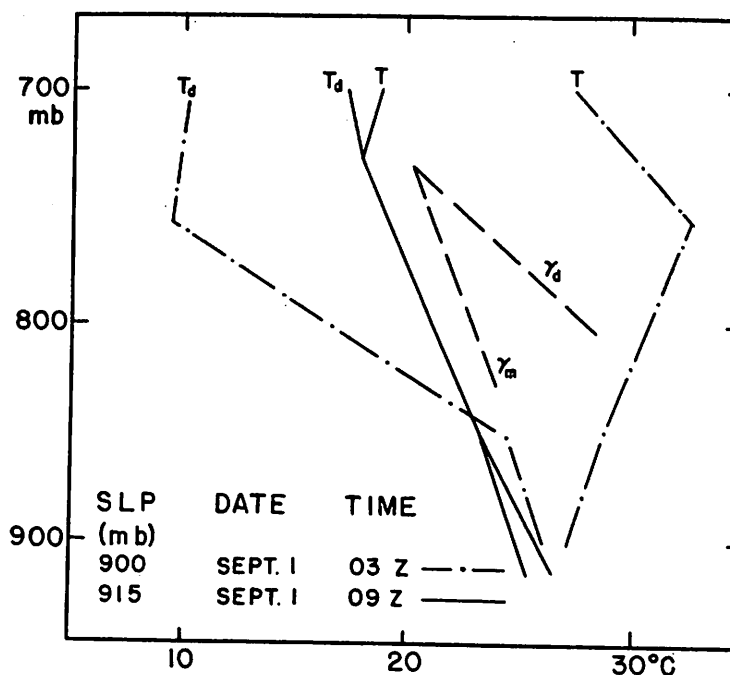
6
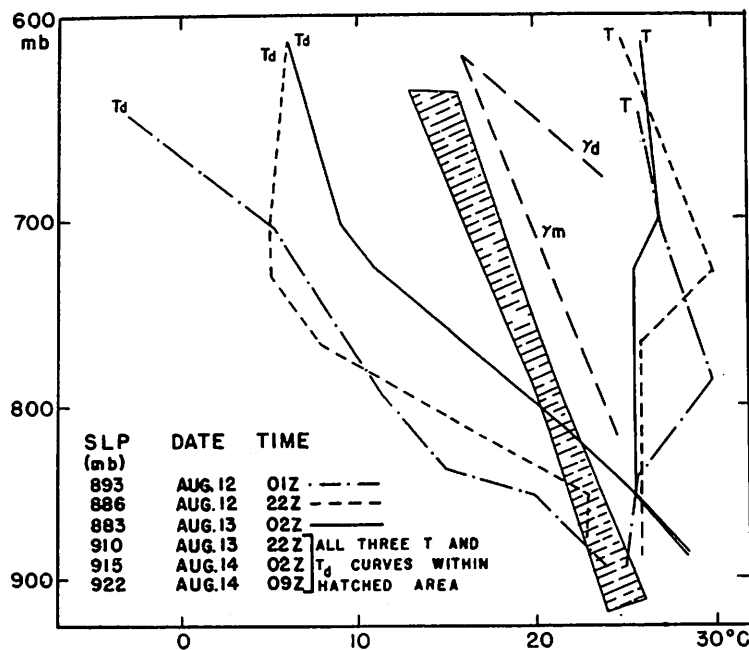
Figure 3. - Temperature and dew point curves from dropsonde observations made in typhoon Nina of 1953 at the times indicated on the diagram. Moist and dry adiabats are shown by the dashed curves.

in figure 2 are real. Additional evidence provided by successive soundings taken in a number of deep storms, as discussed below, suggests that observations of this type not only represent true conditions for the eye but are actually the most common type of sounding during the filling stage of deep storms.

A series of soundings made in typhoon Nina of 1953 show, in a very striking manner, a pattern of warm, dry conditions during the period that the sea level pressure was very low and still decreasing and moist, cool conditions after the time of lowest pressure (fig. 3). In this case, three observations made over a 25-hour period, as the storm was deepening from 893 to 883 mb., showed nearly isothermal lapse rates with extremely low dew point temperatures. In contrast, three soundings made during an 11-hour period, beginning 20 hours after the latest of the dry soundings, were considerably cooler and much more moist. The temperature and dew point curves for the three later soundings all fell completely within the hatched area of figure 3. The consistent behavior within the two periods offers strong evidence that the reported changes in the lower troposphere are real. At higher levels warm temperatures must have persisted during the later period since the sea level pressure was still quite low (910-922 mb.).

Soundings of the type presented above for typhoons Grace and Nina strongly suggest that there are basic differences in the low level temperature and moisture distributions within the eye of a deep tropical cyclone between the deepening and filling stages. In the following section, data from a number of tropical cyclones have been studied in an attempt to determine the extent to which the marked patterns exhibited in these selected cases show up in a larger sample. Only those storms with extremely low central pressures could be considered since it is only in these cases that the warm, dry conditions appear

Table 1. - A tabulation of central pressure (SLP), date-time, and center loca-
tion at the time of minimum pressure of typhoons with sea level pressures
as low as 900 mb. The letters shown after the individual typhoon names
are used in identifying the curves in figures 4, 5, and 7.

Storm	Year	SLP (mb.)	Date and Time (GMT)		Location (°N.lat., °E. long.)	
Ida (I)	1958	877	24 Sept.	0500	18.9	135.3
Nina (N)	1953	883	13 Aug.	0230	18.7	136.8
Joan (J)	1959	884	28 Aug.	2100	21.1	125.2
Ida	1954	888	28 Aug.	0145	20.3	134.7
Vera (Ve)	1959	894	23 Sept.	0600	19.6	142.9
Virginia (Vi)	1957	895	22 June	0900	15.0	127.8
Lola (L)	1957	897	16 Nov.	0800	13.7	140.4
Hester (H)	1957	898	8 Oct.	0200	22.3	141.9
Grace (G)	1958	900	1 Sept.	0300	16.9	130.8
Marge	1951	900	15 Aug.	0200	19.7	136.0

with any regularity below the 700-mb. level; i.e., within the portion of the
atmosphere normally sampled by the dropsonde observations. The detailed
examination of the soundings reported in the next section was, therefore,
limited to tropical cyclones which attained central sea level pressures of 900
mb. or lower.

3. SUMMARY OF SOUNDING DATA FOR UNUSUALLY DEEP TYPHOONS

Dropsonde data for tropical cyclones have been available on a routine
basis for about ten years and in recent years these observations have been
frequent enough so that the day-to-day changes in the central pressure of most
tropical cyclones are fairly well known. A search of the records for the
period 1950-1959 revealed that at least 10 typhoons attained sea level pres-
sures of 900 mb. or lower (table 1). During this period, none of the Atlantic
tropical cyclones (hurricanes) attained sea level pressures as low as 900 mb.
It was found that of the sample of typhoons shown in table 1, there were two
cases (Marge of 1951 and Ida of 1954) in which the dropsonde data were not
complete enough to establish the day-to-day variations in the central sea
level pressure throughout the most intense portion of the storm. The pressure
profiles for the other eight cases, plotted about the time of lowest central
pressure, are shown in figure 4. The time of lowest reported pressure has
been used as the zero hour in this diagram although in some cases symmetry
might suggest that the lowest pressure occurred somewhat earlier or later than
this time, for example, Lola (L) and Ida (I).

The individual typhoons listed in table 1 all attained their lowest sea
level pressures between 13° and 23° N. latitude and most of them were located
in areas far removed from any land. Virginia (Vi) was closest to land, about

200 mi. northeast of the central Philippines. Joan (J) was about 250 mi. northeast of northern Luzon and a similar distance east of Formosa.

An attempt was made to select soundings in a prescribed manner to represent the deepening and filling stages of each of the storms shown in figure 4. The times of the soundings selected to represent the deepening stage are shown by the arrows to the left of the time of lowest pressure on figure 4. These observations were all made near the end of the period of most rapid deepening and, in all cases except one, prior to the time of lowest pressure. In most instances these were made within 6 hours of the time of lowest pressure, but in Nina (N) and Lola (L) the time difference is more than 24 hours. In one case, Hester (H), the sounding at the time of lowest reported pressure has been used since there were no earlier soundings made during the period of rapid deepening. In this and other cases, there is some question whether the sea level pressure was actually falling at the time of the selected observation. The maximum rate of deepening for the eight storms computed from successive observations varied between 5.8 mb./hr. over a 14-hour period in Ida (I), and 2.4 mb./hr., over a 19-hour period in Joan (J).

The first sounding made after the one showing the lowest sea level pressure was chosen in each case to represent the filling stage of the storm. These cases, shown by the arrows to the right of the zero time position on figure 4, were distributed from 3 to 25 hours after the lowest pressure. In some cases a second period of deepening was observed. These have been ignored except in the case of Nina (N) where the lowest central pressure occurred during the second deepening period. No attempt has been made to recompute all the individual dropsonde records and some of the smaller irregularities in the curves may have arisen from erroneous reports.

The temperature values for the individual soundings marked by the arrows in figure 4 are plotted as deviations from 25°C. in figure 5. On this diagram, the temperature sounding for the deepening stage in each individual storm is plotted directly above the sounding representing the filling stage. It is seen that in most cases the temperatures were considerably warmer during the deepening stage with the greatest differences in the upper portion of the soundings. The indicated cooling in the filling stage was in excess of .8°C. at some level between 700 and 800 mb. in six of the eight cases. Even greater differences could have been obtained in some storms by selecting other soundings; for example, the soundings made at the time of lowest pressure in Joan (J) and Grace (G) were up to 5° C. warmer through deep layers than those shown for the deepening stage in figure 5. None of the soundings made in Virginia (Vi) revealed the relatively warm, dry eye conditions found during the deepening stage in the other cases. No explanation has been found for the fact that Virginia appeared to behave differently than the other storms.

In the deepening cases other than Virginia and Joan, the 750-mb. temperatures shown in figure 5 are from 7° to 10°C. warmer than could have been obtained by parcel ascent from the surface. In the filling cases, none of the 750-mb. temperatures indicated on figure 5 are more than 2° C. warmer than could have been obtained by parcel ascent, and in six of the eight cases differences from the parcel ascent value are less than 1°C. Larger departures were shown at the 700-mb. level since, as shown in figure 5, several of the soundings tended to show greater stability near 700 mb. than at lower levels.
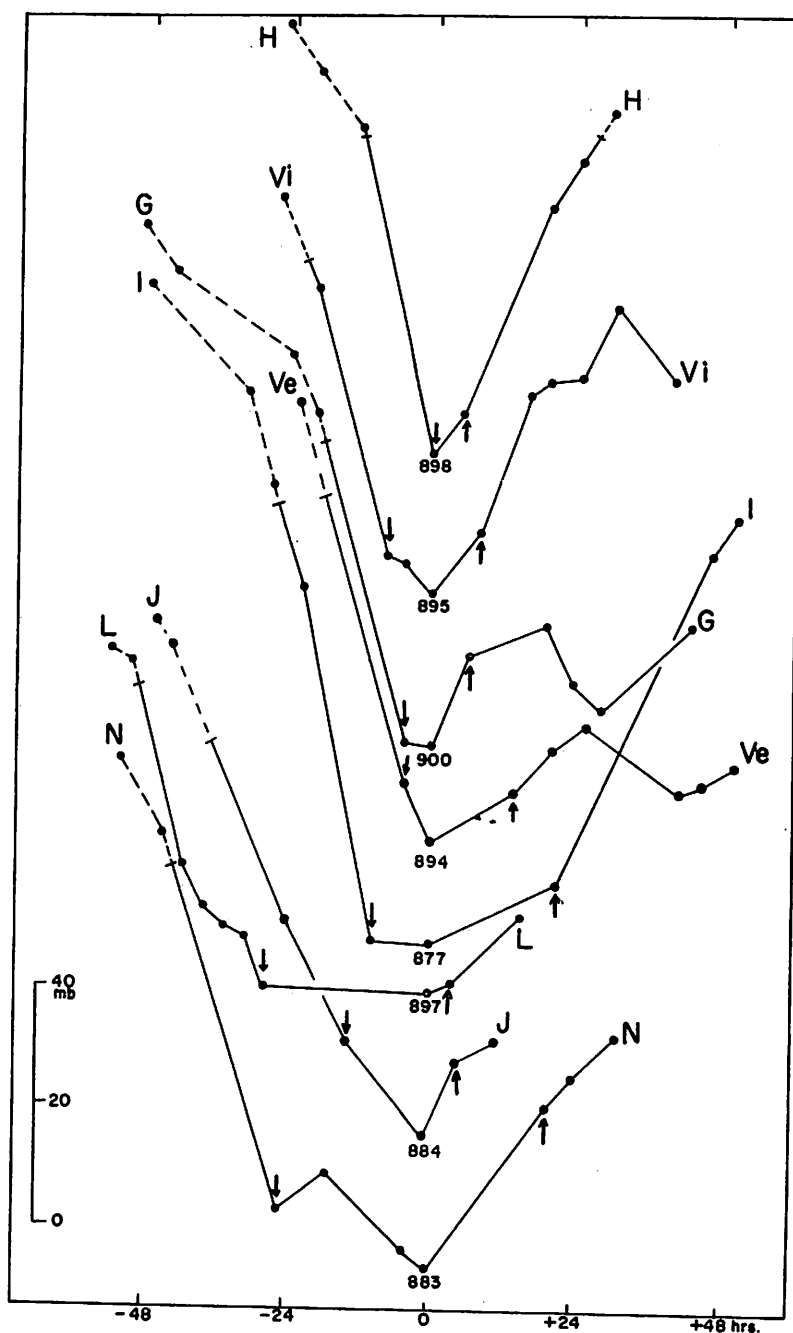
Figure 4. - A plot of central sea level pressure vs time for the eight deep
typhoons with all curves centered about the time of lowest pressure. The
identifying letters correspond to those shown in table 1. The dashed por-
tion of the curves correspond to sea level pressures greater than 950 mb.
and a pressure scale applicable to all curves is shown in the lower left.
The minimum pressure is shown in millibars below the minimum point of each
curve. The arrows at or to the left of the minimum point of the curves in-
dicate the observations selected to represent the deepening stage of each
typhoon; arrows to the right of the minimum point indicate those used for
the filling stage in each case.
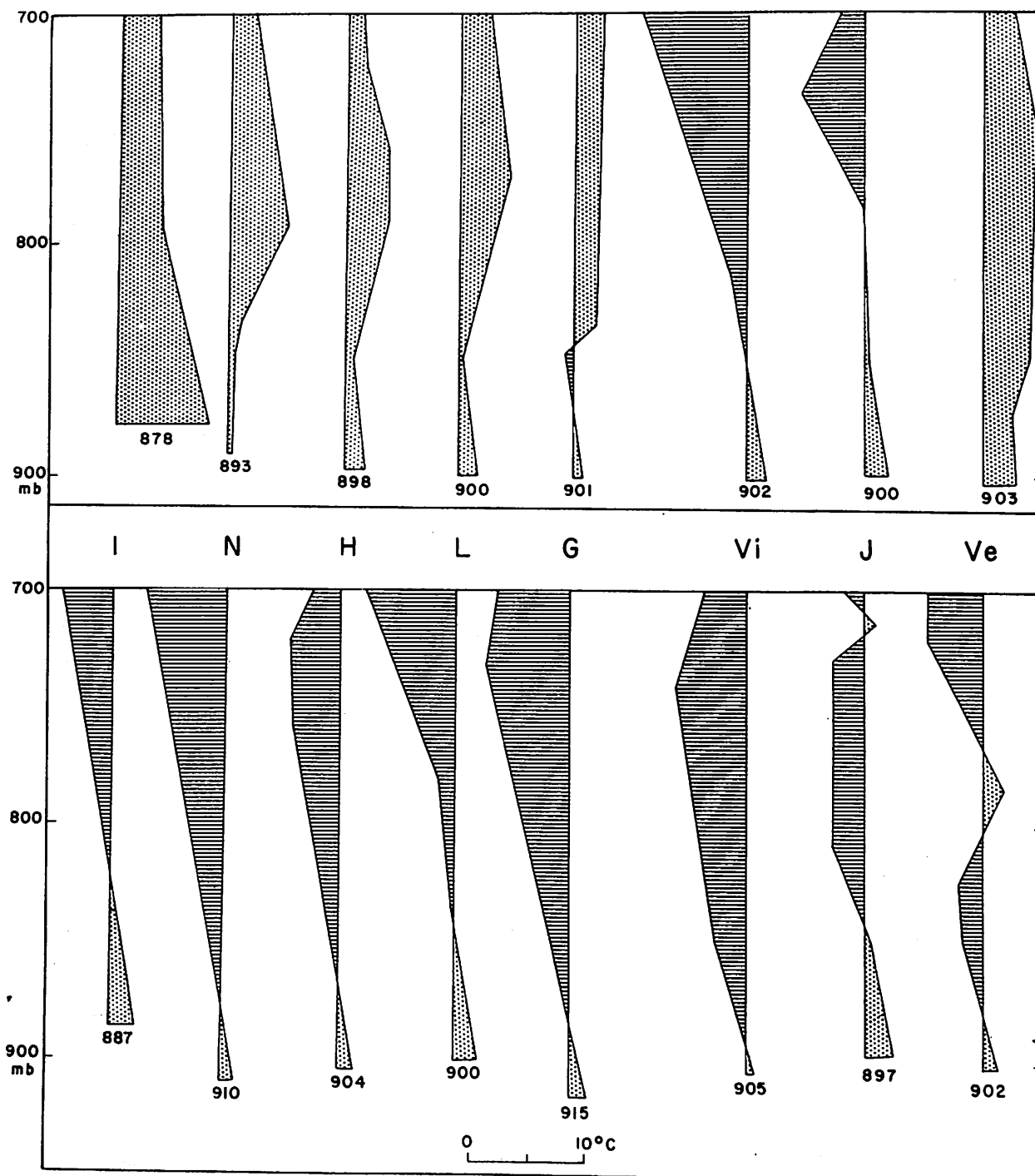
Figure 5. - Temperature data from the deepening and filling soundings, indicated in figure 4, shown as deviations from 25° C.; i.e., the stippled areas represent layers warmer than 25° C. and the hatched ones layers colder than this value. A temperature scale applicable to all curves is shown at the bottom of the figure. For each typhoon, identified by letter, the upper curve is applicable to the deepening stage and is plotted directly above the one for the filling stage.
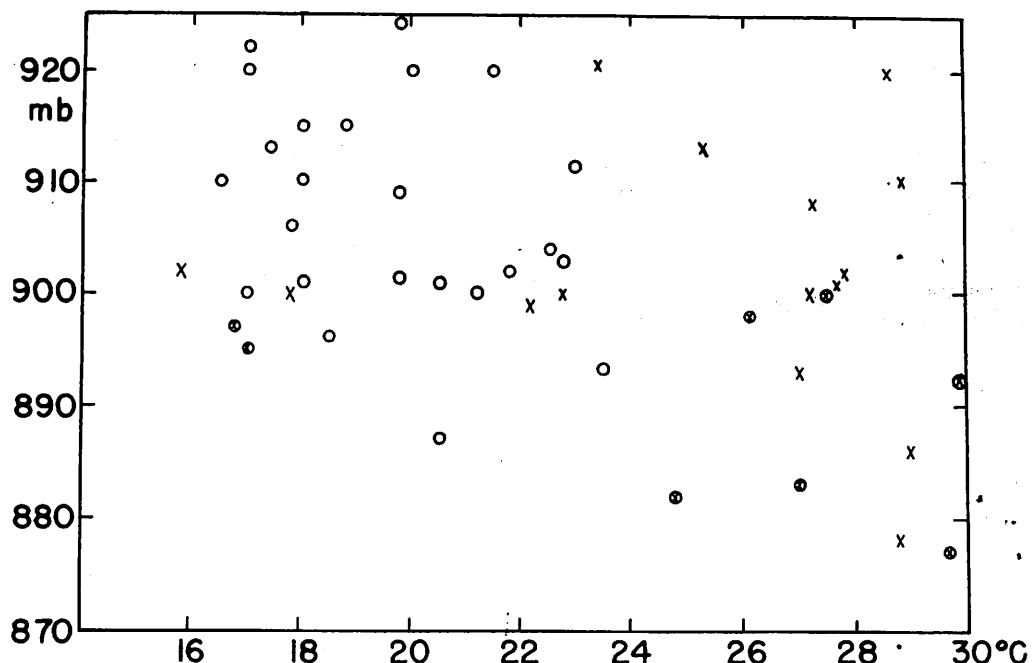
Figure 6. - A plot of the 700-mb. temperature against the central sea level
pressure for all dropsonde observations made in the eight typhoons shown in
figure 5 during the periods when the central pressure was 925 mb. or lower.
The observations made prior to the time of lowest pressure are indicated by
crosses, those made after this time are shown as circles, and the observa-
tions at the times of lowest pressure are shown as crosses within circles.

This tendency would be expected to be more pronounced at higher levels since,
as pointed out previously, large positive temperature anomalies must be pre-
sent at the upper levels to account for the low central pressures.

The 700-mb. data from all the dropsonde observations made in the eight
deep typhoons during the periods when the sea level pressure was less than
925 mb. (fig. 6) show the same pattern as given by the data from the selected
soundings presented in figures 4 and 5. All cases with 700-mb. temperatures
warmer than 24° C. occurred at or before the time of lowest pressure and 20 of
the 24 cases of 700-mb. temperatures less than 22°C. occurred after the time
of lowest pressure.

The changes in moisture content of the air within the eye between the
deepening and filling stages have been studied by preparing curves of the mix-
ing ratio for the soundings taken at the times marked in figure 4. The mixing
ratio curves which are shown in figure 7 have been plotted as deviations from
18 g./kg. Comparison of the upper set of curves with the lower one suggests
that, in most cases, the eye is considerably drier during the rapidly deepen-
ing stage but not all soundings made during this stage reported dry conditions.
Some of the dry cases correspond to relative humidities as low as 15 percent
with fairly deep layers in which relative humidities were less than 30 percent.
Some of the moist cases reported saturated conditions throughout the sounding.

The deepening sounding for Hester (H) showed very high mixing ratios

Figure 7. - A plot of mixing ratio from the deepening and filling soundings prepared in the same form used for temperature in figure 5. The stippled areas represent layers with a mixing ratio greater than 18 g./kg. and the hatched ones those with a mixing ratio less than this value. Humidity data for the fill- ing sounding of Virginia (Vi) were missing at most levels and have not been entered.
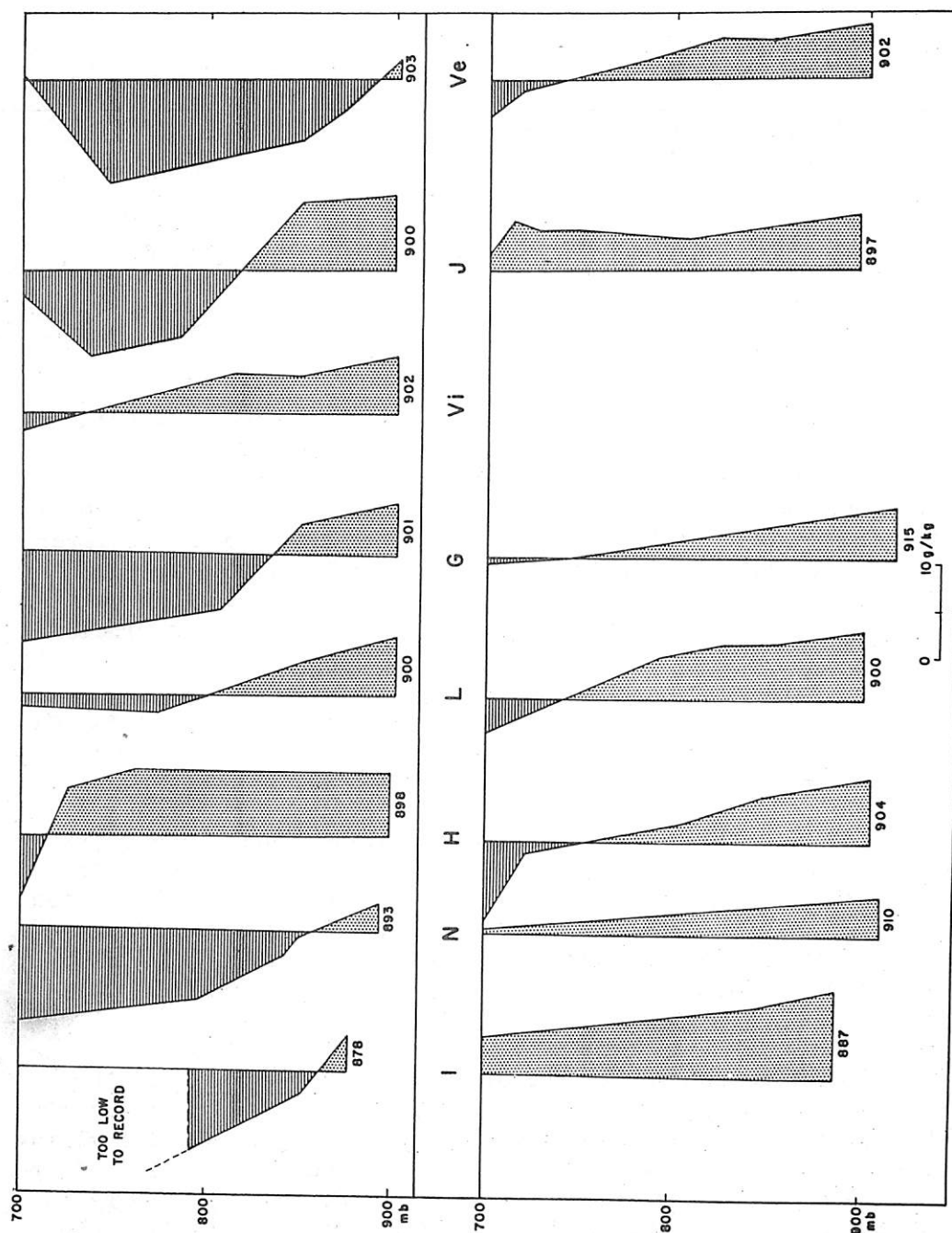
below the 750-mb. level but in this case the lowest pressure may well have occurred prior to the time of this observation. There were no other soundings made during the period that the sea level pressure fell from 952 mb. to the minimum value of 898 mb. (fig. 4). A relatively high moisture content was shown on all observations made during the deepening stage of Virginia (Vi) and, as mentioned above, temperatures in this storm were much lower during this stage than in the other cases presented. Moisture data were missing at most levels in the sounding chosen to represent the filling stage in Virginia. However, later observations - as well as the earlier ones - showed nearly saturated conditions throughout the surface to 700-mb. layer.

Several of the soundings in figure 7 show the mixing ratio decreasing rather rapidly above the 750-mb. level. Within this upper portion of the soundings, there was also a tendency for more stable lapse rates (fig. 5). These two effects suggest that the descending air within the typhoon eye often penetrated very little below the 700-mb. level even in the very deep typhoons. In tropical cyclones with somewhat higher central pressures, the dry air seldom penetrates below the 700-mb. level but dry conditions have been noted quite frequently in the 700-mb. to 500-mb. layer [4]. Dropsonde data from the 500-mb. level have not been available on a routine basis and most of the data of this type have been gathered in Atlantic storms with central pressures greater than 960 mb. In many of these cases dry air was not present in the eye even at the 500-mb. level.

The data from typhoon Ida of 1958 presented in figures 5 and 7 are very interesting in that they suggest that the warm, dry descending air in the eye actually reached the surface level. The surface temperature was reported as 33° C. (92°F.) and the relative humidity was roughly 50 percent. Both of these values represent very unusual conditions over the tropical oceans. The extremely low pressure recorded on this sounding (878 mb.) was only 1 mb. higher than the all-time record minimum sea level pressure which was observed 8 hours later in this same storm [7]. To the knowledge of the writer, this sounding is the only documented case of warm, dry surface air in the eye of a typhoon over the open ocean; however, rare cases of marked warming and drying have been reported during the passage of tropical cyclones at land stations [14].

4. VISUAL FEATURES OF THE EYE

The selected soundings from the eight deep typhoons discussed above indicate that rather marked changes in the temperature and moisture distributions in the lower portion of the eye occur at about the time of lowest pressure. It would seem likely that changes of this type must be accompanied by systematic changes in the extent and type of cloudiness within the eye and perhaps by changes in the size of the eye. Therefore, an attempt was made to utilize the reconnaissance observations to investigate changes in the visual features of the eye between the deepening and filling stages of the eight deep typhoons.

Cloudiness: The amount of cloud information for the eye given by the reconnaissance reports varies considerably, depending mainly on the interest of the observer. Cloud observations for the eye are seldom reported in the standard reconnaissance code since information of this type would have little

value. This is because cloud observations refer to conditions within a circular area 60 miles in diameter centered on the aircraft and, therefore, normally include the wall clouds surrounding the eye. The remarks included in the plain language descriptions of the eye, which are normally a part of the reconnaissance reports, can be used in studying the cloudiness; but these are often incomplete. In many cases the observers describe special features of the clouds without giving a complete report on cloudiness at all levels. Some of the remarks from the reconnaissance forms discussed below illustrate the difficulties which arise in using information of this type.

The remarks listed in figure 8 have been taken from the reconnaissance reports for the eye of the eight deep typhoons. In some cases, the descriptions of the eye give little or no information on cloudiness. For example, at the time of the deepening sounding in typhoon Ida which suggested that the descending motion had reached the ocean surface, the only information given was: "eye well-defined." This remark clearly suggests diminished cloudiness but may also have been prompted to some extent by the organization of the clouds which may have been present in and around the eye.

The information given in figure 8, although spotty, indicates quite definitely that cloudiness is prevalent within the eye. There is very little indication that the cloudiness is greater during the filling stage as might be expected from the indicated changes in temperature and humidity. The eye was described as "well-defined" in three cases prior to the time of lowest pressure, but there were also two cases of altostratus overcasts reported during periods of rapid deepening.

The cloudiness indicated for the eight deep typhoons is no more extensive than is normally found in the eye of tropical cyclones.[1] The popular accounts give a completely different impression in regard to the extent of cloudiness, and even a recently published meteorological text [15] included the following description of the eye: "... within the eye of most intense hurricanes the skies clear almost completely, and without exception the eye is free of precipitation and completely cloudfree at all intermediate levels." In contrast, a study of Gulf of Mexico hurricanes published in 1926 [1] led to the following conclusion: "... there is not a single instance of record in any of these sixteen cyclones to indicate the semblance of an 'eye of the storm,' as an area of little or no cloudiness."

The reconnaissance observations lead to a picture of cloudiness in the eye intermediate to the views expressed by the above quotations and show quite clearly that the extent and type of cloudiness within the eye is highly variable. In view of this variability and the incomplete nature of the cloud observations, perhaps it is not surprising that the cloud information presented in figure 8 indicates no clear cut differences between the deepening and filling stages.

Size of the Eye: The reconnaissance observations give fairly reliable reports on the size of the eye on nearly all penetrations of the storm core.

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[1] As shown by an unpublished study made by the author based primarily on typhoon data for the 1952-1954 period.

hrs	IDA 877 mb	VIRGINIA 895 mb	LOLA 897 mb	NESTER 898 mb	GRACE 900 mb	JOAN 884 mb	VERA 894 mb
-48	Filled with sc and cs					Overcast as 15,000	
-36			Filled with cu, tops 5000; stars visible overhead; Frequent lightning		Filled with cu, tops 7000	Thin high as in eye; sc in concentric circles tops 5000	
-24	Broken clouds below; broken ac and ct above; Broken sc below thin overcast ct above	Practically filled with sc	Eye well-defined	Filled with cu; as overcast; Filled with cu; as overcast	Sc below and as above	Frequent lightning; 4/8 sc tops 5000; thin as above; Filled with sc; overcast as at 14,000	
-12	Eye well-defined			Eye well-defined; Lightning	Filled with low broken clouds	Brkn as over eye	Thin as overcast, 17,000
0	Layer of cu and as in eye	Completely filled with sc	Completely filled with "rope" clouds to flight level	Almost completely filled with cu	Sky chaotic	Cu in eye; open above	Clear area above eye 10 mi diameter; 7/8 sc tops 4500
+12		Filled with cu and sc	Filled with cu, tops 4000			8/8 cu below, tops 6000-11,000; clear above; 8/8 cu tops 7000; Clear above	Clear above, broken sc below
+24	Moderate turbulence in eye; Filled with clouds tops 8000				Filled with clouds		7/8 cu tops 7000; Overcast as over eye
+36	Filled with clouds tops 12000; Filled with cu	Filled with cu		Filled multiple layers as	Filled with clouds heavy cu in center of eye; blue sky above		Filled with cu, tops 6000-8000; Breaks in ci above eye
+48 hrs	Filled with clouds	Filled with cloud; large cu in center	Filled with cloud below and above flight level (8000 ft)		Filled low broken clouds and broken middle and high clouds		Chaotic sky in eye

Figure 8. - A listing of remarks from the reconnaissance reports concerning cloudiness and special features of the eye of the eight deep typhoons considered in this report. The remarks are entered according to time on a scale extending approximately 50 hours prior to and following the time of the lowest pressure. The zero point of this scale corresponds to that shown in figure 4. Information of the type entered here was not available for typhoon Nina and was available only for a short period following the lowest pressure in typhoon Joan of 1958. Standard abbreviations have been used for cloud types; i. e., as for altostratus, sc for stratocumulus, etc.

These are usually based on radar observations but in well-developed storms the differences in size between the eye as defined visually from levels of 8,000 to 10,000 ft. and as given by radar are quite small. Elliptical eyes are often reported in weaker storms but in the deep cases the asymmetries are usually are usually very small and it is rare when a shape other than circular is reported.

The eye of tropical cyclones tends to be smaller in the deeper storms. This is shown by table 2 which is taken from an unpublished study by the author, based mainly on typhoon data for the 1952-1954 period. Nearly two-thirds of the observations in storms with sea level pressure less than 920 mb. reported the eye less than 20 miles in diameter and there were no cases in excess of 30 miles. In contrast, in the weaker storms up to about one-third of the values were in excess of 30 miles. Six of the eight deep typhoons discussed in this report had eyes 15 miles or less in diameter at the time of lowest pressure and none was greater than 20 miles.

Data from 24 typhoons which occurred in the 1952-1954 period and those from the eight deep typhoons were analyzed in an attempt to determine if there are systematic changes in the size of the eye between the deepening and filling stages. This larger sample included data from relatively weak storms as well as intense ones. The changes in eye diameter during the day preceding and following the time of lowest pressure are shown in table 3. As discussed earlier, the actual time of lowest pressure may have been several hours earlier or later than the time of the lowest observed pressure. However, as in the preparation of figure 4, the time of lowest observed pressure was used in each case as the dividing point between the deepening and filling stages. The eye diameter reported at this time has been compared with that reported on the previous and following days. Data for the previous and following days were

Table 2. - A tabulation of the percent of observations of eye diameter which fell into the four listed size divisions for each of the four indicated ranges of sea level pressure. These observations are from typhoons during the 1952-1954 period and from the eight deep typhoons considered in this report.

Eye Diameter (mi.)	Sea Level Pressure (mb.)			
	≥980	979-950	949-920	<920
	(percent)			
0-10	21	21	26	33
11-20	33	27	19	39
21-30	25	21	21	29
> 30	20	31	34	0
No. of cases	118	118	77	55

Table 3. - Changes in eye diameter between the day prior to and the day of lowest pressure $(\triangle D)_1$ and between the day of lowest pressure and the following day $(\triangle D)_2$. The larger sample is taken mainly from typhoons during the 1952-1954 period.

	$(\triangle D)_1$			$(\triangle D)_2$		
	Increase	No change	Decrease	Increase	No change	Decrease
All cases	8	2	21	21	4	4
SLP $\leqq$ 900 mb.	2	1	5	5	1	1

selected by using the observation made closest to the same time of day as the observation of lowest pressure, and only those observations made more than 18 hours and less than 30 hours from the zero hour were included. The data presented in table 3 show that in a large percentage of cases the eye diameter decreased on the last day of the deepening stage. This occurred in 21 of 31 cases in the total sample and in 5 of 8 cases in the deep typhoons. The median value of the change during this period was a decrease of 5 miles. During the day following the lowest pressure, 21 of the 29 cases showed an increase of eye diameter with a median value of 8 miles. Five of the deep typhoons showed an increase of eye diameter during this period. In view of the difficulties in evaluating the eye size and in specifying the time of lowest pressure, the above statistics show a surprising degree of consistency and suggest that in a large proportion of deep storms the eye can be expected to decrease in size during the final period of deepening and to increase rather quickly following the time of lowest pressure.

5. SUMMARY AND CONCLUSIONS

The observations examined in this report indicate that warm, dry conditions, undoubtedly arising from subsidence, occur frequently within the lower tropospheric portion of the eye of unusually deep typhoons during the rapidly deepening stage of the storm. There is some evidence that, in the extreme cases, the descending motion may reach the surface of the earth. Apparently, the descent into the lower portion of the eye is interrupted at or near the time of lowest pressure and, following this time, there is a marked change toward lower temperature and higher moisture values. Although temperature changes in the surface to 700-mb. layer are often quite large between the deepening and filling stage of deep typhoons, the changes within this layer offer a relatively small contribution to the total pressure change. Even in the extreme cases, the contribution of this layer is of the order of 10 mb. and often, especially during the filling stage, the temperature distribution in this lower layer remains virtually constant during periods when the sea level pressure changes by 50 mb. or more. Therefore, with data from only the lower portion of the eye, very limited deductions can be made in regard to the formation and maintenance of the thermal distribution within the eye. There is no doubt, however, that abnormally warm temperatures must persist at upper tropospheric levels during much of the filling stage in order to account for the low sea level pressures.

It might be argued that, once formed, the reservoir of warm air in the upper troposphere might move along with the storm center with only small radiational losses. If this were true, low sea level pressures could be maintained for considerable periods with only weak subsidence at upper tropospheric levels within the eye. There is, however, little reason for believing that a marked change in the upper tropospheric circulation patterns in the eye should necessarily accompany the observed changes in the temperature and moisture distributions below the 700-mb. level. We know that, in all except the deepest tropical cyclones, there is very little temperature increase in the surface to 700-mb. layer during the deepening stage, although there must be substantial increases at higher levels to account for the large decreases in sea level pressure. We also know that in the middle troposphere in cases of this type convective scale descending motion may be present around the rim of the eye [8].

Temperature lapse rates in the eye during the rapidly deepening stage of the deep typhoons are considerably more stable than the moist adiabatic rate. However, during the filling stage the observed temperature distribution below the 750-mb. level can be accounted for fairly closely by postulating moist adiabatic parcel ascent from the surface, and, in most cases, the actual conditions are such that only small departures from saturated conditions are indicated. However, the observed change toward lower temperature and higher moisture values can probably be accomplished without having organized ascending motion throughout the eye. A marked increase in evaporation of cloud material within the eye could presumably bring about such a change toward cooler temperatures and higher humidities. In fact, a reduction of the temperatures shown during the deepening stage (fig. 5) to their wet bulb values throughout the 700-mb. to surface layer would be more than adequate to account for the observed cooling in the individual cases. For the evaporative process to assume an important role, it would seem that it would be necessary for much of the same air to remain in the eye for periods of at least several hours. On the other hand, if the temperature distribution is to be accounted for by ascent, there is much less restraint on the exchange of air between the eye and its surroundings, at least in the layer very near the surface.

The reconnaissance observations from the eye as illustrated by the remarks presented in figure 8, suggest that the eye is often filled with cloud below flight level. We do not know to what extent cloud material mixed into the eye from the wall cloud may be important in maintaining the observed patterns of stratocumulus cloudiness within the eye. These clouds are based at very low levels, in some cases lower than 600 ft. [12], appear to be relatively stable, and, as indicated by some of the remarks, often show well-marked organization as concentric bands or "ropes." This type of stable organization and the very low cloud bases might offer some support for the lateral mixing hypothesis. On the other hand, the clouds are often better developed and higher in the center of the eye and are relatively weak just inside the wall cloud; Simpson [13] has used the descriptive terms "hub cloud" and "moat" in referring to those features. This pattern, of course, suggests descending motion around the rim and ascent in the interior of the eye.

Convective type clouds can, of course, be present in areas where the mean motion is downward. However, if this type of circulation existed within the eye it would seem that a rather definite layer of temperature increase

and moisture decrease would correspond closely with the cloud tops. In fact, the moisture in the eye during the filling stage is often quite high at the 700-mb. level although the clouds seldom extend to this level.

The above discussion suggests that the observational material presented in this report probably offers little direct assistance in deducing details of the circulation patterns in the eye of a tropical cyclone during the different stages of the storm development. However, these observations may prove to be of value if used in connection with theoretical models aimed at explaining the formation and maintenance of the eye. The analysis carried out in this report has shown that certain of the observed features of the eye of deep tropical cyclones take on a great deal more meaning if viewed in relation to the life cycle of the storm. This can perhaps be taken as encouragement that other features of these storms which now appear to be so lacking in organization may also fit into reasonable patterns if viewed within the proper framework.

ACKNOWLEDGMENTS

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